Targeting the integration of multi-period utility systems for site scale process integration

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Abstract

A method to target the optimal integration of the utility system within a chemical production site for multi-period operations has been developed. This paper is organised in three parts,

After introducing the type of problem to be solved, the first part report about the mathematical model used to solve the integration problem when the production specifications of the processes in the industrial site are constant (here average production levels).

In the second part of the paper, the multi-period utility requirements of the chemical processes are analysed. A optimisation problem is stated to compute the multi-period load scenario that defines the utility requirements with a minimum number of operating periods sets covering satisfactorily the yearly operation of the total site. A genetic algorithm is used to solve this problem. Furthermore, the generic mathematical formulation of the multi-period utility targeting is provided, including the possibility to deal with different sets of technologies for the synthesis of the utility system.

The third part of this communication presents the results obtained for a realistic problem described in the introduction. Discussion of the limits and the powerful features of the method developed are shortly presented.

Key words: Process integration, Combined heat and power, Multi-period integration, Utility system, process synthesis, Site scale optimisation, cogeneration

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1 Introduction

Energy integration studies rely on the definition of the energy requirements at the nominal conditions. If the definition of such base case for a single process is usually easy to obtain, the problem becomes much more complex when the energy integration concerns site wide problems. Consider as an example a chemical site that includes 5 integrated chemical processes, the goal being to define the optimal cogeneration system to be considered for this chemical industrial site. Considering the nominal production levels for each of the subsystems (processes), we define their energy requirement by a list of hot and cold streams (in the example the total number of process streams is about 60). Figure 1 shows the nominal composite curves of the five processes of the production site. Such data will allow to compute the possible energy savings by heat exchange inside the processes or between the processes.

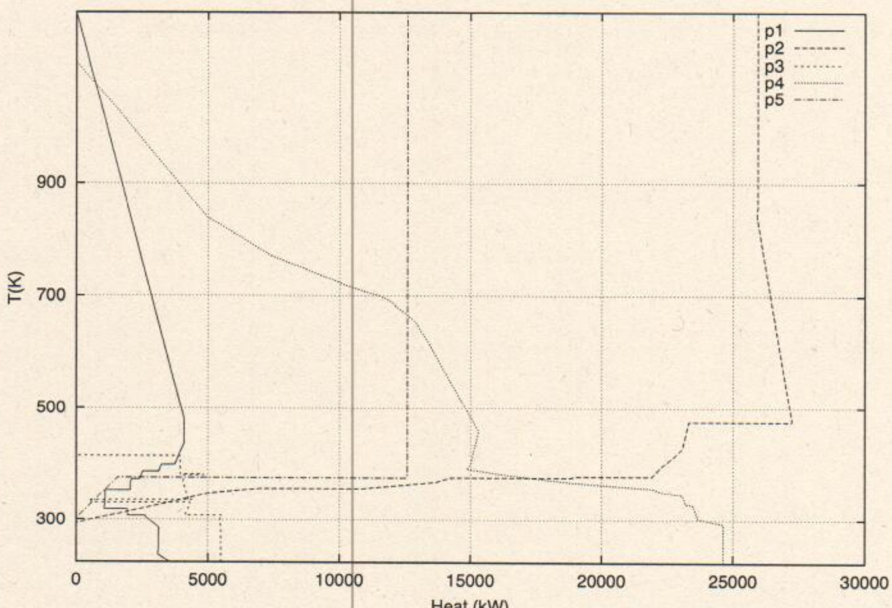

Fig. 1. Grand composite curves of the five processes concerned

Furthermore, the problem will concern not only the process-process heat exchanges but also the integration of the utility system and the possible use of different technologies in the utility system : combined heat and power production using steam turbines, cogeneration units, organic Rankine cycles, refrigeration systems, heat pumps, etc... In such cases, one has to consider not only the nominal operating conditions of each process but also the possibility for these conditions to vary with time. In the process real life, the operating conditions and the environmental conditions to be considered over one year period (or more) may vary from one process to another and from time to time, making the optimal utility system design much more complex. These variations correspond for example

(1) to variations of the production level of the processes with respect to the market conditions;
(2) to market conditions variations, e.g. electricity price vary with day time and with seasons;
(3) to production shifts or batches;
(4) to efficiency variations with respect to the ambient conditions;
(5) to maintenance of the equipments;
(6) to discontinuous operation of the processes.

Figure 2 shows the measured dayly production levels of the 5 processes studied for a period of one year. We come back to figure 2 here after.

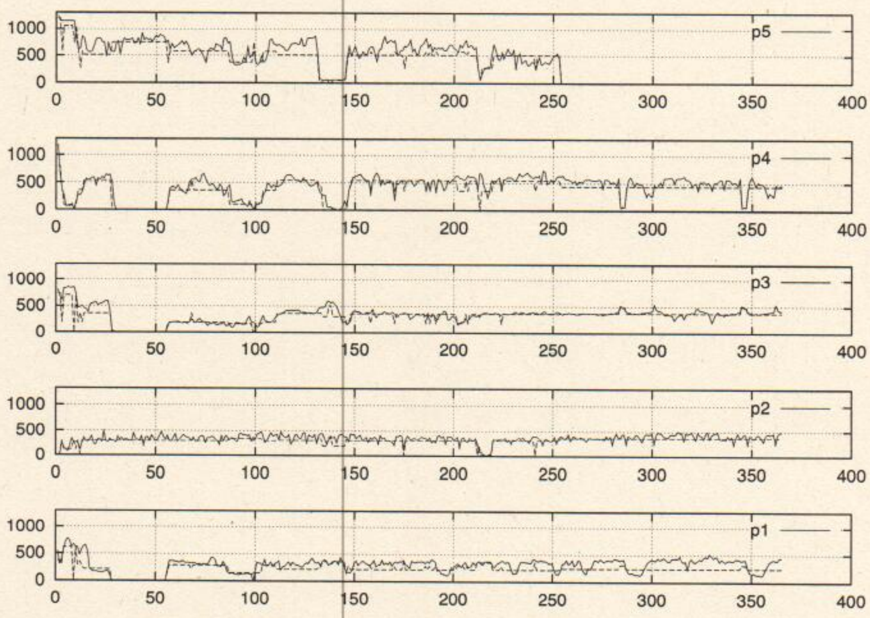

Fig. 2. Variation of the process levels with time and the selected levels

In the developed approach, we considered that the process requirements of the site has been obtained by multiplying the flow of the hot and cold streams defined in nominal conditions by the corresponding level of utilisation at time t. This simplifying approach may be fine tuned in order to allow the use of specific streams definition at each time to account for the influence of the ambient temperature or the process material integration (effect of the process operating conditions on other processes). Figure 1 shows the mean Grand composite curve obtained by averaging the level of utilisation of each sub-system (process) over the operating time period.

In order to be able to synthetize the heat exchanger network, one first defines the complete list of hot and cold streams to be considered. This means that the utility system has to be considered together with the heat recovery network and that the utility flowrates have to be adapted at each time period because we have to consider the possible integration of the cogeneration units, the combined heat and power production with the steam network, the cooling system, the refrigeration system, the possible use of a heat pump, etc.

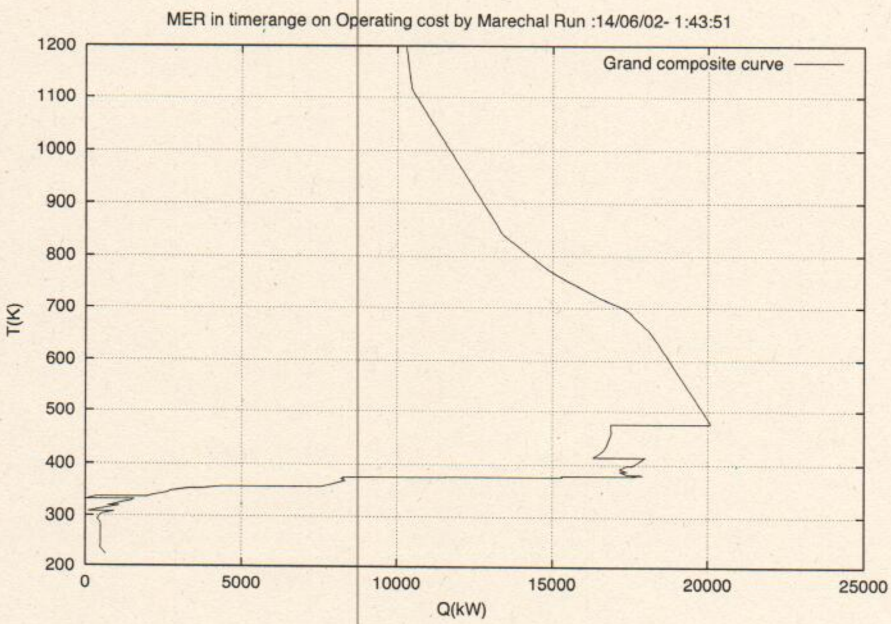

Fig. 3. Average composite of the integrated production site

2 Combined heat and power systems

Targeting the optimal integration of utility systems in the frame of the combined heat and power production has already been tackled by the authors and a modeling framework has been developed. It includes gas turbine and combustion system model (Marechal and Kalitventzeff , 1998), the steam network (Marechal and Kalitventzeff , 1999), the refrigeration system (Marechal and Kalitventzeff , 2001) and the organic rankine cycles (Marechal and Kalitventzeff , 2001). Each technology introduces a set of equations considered together into a super-structure model to define a Mixed Integer Linear Programming (MILP) problem. In order to incorporate realistic market conditions for the technologies, the method will be extended here to incorporate the specific characteristics of the selected technologies stored in technology data bases reflecting the market conditions. This appeared to be necessary to represent standard sizes technologies like gas turbines or gas engines (Kalitventzeff and Marechal , 2000). The following algorithm has been developed :

- from the average composite curve, determine the characteristics of the heat load to be supplied by the cogeneration unit;
- applying selection rules of the experts select in the data base a list of suitable cogeneration units available on the market and that have the potential of satisfying the energy requirements;
- using the technical description of the cogeneration unit in the data base, compute the performances of the equipment according to the environmental conditions (e.g. ambient temperature, fuel composition) with the thermo-economic models. This is done in two steps :

(1) model parameter estimation using the performances described in the technology data base;
(2) using the identified parameters, compute the equipment performances according to the process operating conditions. This calculation is made for each operating period;

- for each period, linearize the partial load performance (fuel consumption, mechanical power production, heat load, ...) as a function of the heat load supplied by the unit.

At the end of the utility system selection procedure, a set of five candidate gas turbines (table 1) has been proposed for the calculation together with a steam network whose temperature and pressure levels are given in table 2. The utility system also includes the cooling water system as well as a refrigeration unit.

Table 1
Catalog characteristics of the selected gas turbines

	El (kWe)	Heat (kW)	η_e %	η_h %	IC K€	OC €/MWh
GT1	5500	8876	31.5	53.5	4438.4	4
GT2	5300	9024	30.1	54.2	4679	5
GT3	10613	15895	32.7	51.3	8710	4.7
GT4	8018	12904	32.0	53.6	6377	4.7

Table 2
Proposed pressure levels for the steam system :
P : header pressure, T header temperature, Tsat : saturation temperature, type : uses of the steam (steam produced (prod), steam consumed in the process (use), steam from condensing turbine (cond))

	P (bar)	T (K)	Tsat (K)	type prod/use
S1	145	867	620	production
S2	54	744	544.7	production/use
S3	11	577.	456.	production/use
S4	4	477	412	production/use
S5	1.5	-	374	use
S6	0.1	-	320	use/cond

2.1 Mathematical model description

The mathematical formulation of the targeting problem is used using the concept of Effect Modelling and Optimisation (EMO) developed by the authors (Marechal and Kalitventzeff , 1998). This is a Mixed Integer Linear Programming (MILP) formulation where each technology in the utility system is considered with an unknown level of utilisation that will be determined to satisfy the heat cascade constraints that define the process heat requirements, the mechanical power production balance as well as additional modeling constraints in order to minimise an objective function that is either operating cost, energy efficiency or total cost including the investment. We will here limit the model description to the integration of the combustion and cogeneration systems. This model represents the integration of the gas turbine including the partial load operation, the possible post-combustion of the gas turbine flue gas, the use of different fuels in the gas turbine and in the post combustion, and of course conventional combustion in a radiative furnace with possible air enrichment or air preheating. This is obtained by adding the following integration constraints.

2.1.1 *Gas turbine and combustion system*

Hot stream corresponding to the outlet of a gas turbine g :

$$Q_g^{gt} = f_g * \dot{m}_g * cpf_g * (TOT_g - Tstack_g) \tag{1}$$

where $\dot{m}_g$ is the flue gas flowrate at the outlet of the gas turbine g in nominal conditions. These values result from the simulation of the gas turbine g

Q_g^{gt} is the total heat load of the fumes from the gas turbine g

cpf_g is the mean cp of the flue gas at the outlet of the gas turbine g

TOT_g is the temperature of the flue gas of the gas turbine g

$Tstack_g$ is the stack target temperature accepted for the outlet of the gas turbine g after heat recovery

f_g is level of utilisation of gas turbine g, $f_g^{min} * y_g \leq f_g \leq y_g * f_g^{max}$

y_g is the integer variable representing the use or not (1,0) of the gas turbine g

$f_g^{min(max)}$ is the minimum (maximum) level of utilisation of the gas turbine g

Hot stream corresponding to the post combustion (heat available for convective heat exchange)

$$Q_g^{pc} = f_g^{pc} * \dot{m}_g * cpf_g * (Trad - TOT_g) \tag{2}$$

where $Trad$ is an arbitrary temperature used in the combustion model representing the limit of the radiative exchange

f_g^{pc} is the fraction of the nominal gas turbine flue gas flowrate used for post combustion

Q_g^{pc} is the supplementary heat load supplied by the flowrate fraction of the flue gas flowrate of gas turbine g used in the post combustion device

Fuel consumption

$$\sum_{c=1}^{n_{cgt}} f_c^g * LHV_c - \sum_{g=1}^{n_g} y_g * FCI_g + f_g * FCP_g = 0 \tag{3}$$

where	n_g	is the number of gas turbines proposed in the utility system super configuration
	n_{cgt}	is the number fuels available for combustion in the gas turbines
	LHV_c	the lower heating value of the fuel c
	f_c^g	the flowrate of the fuel c in the gas turbine g

Electricity production with the gas turbines W_{gt}

$$W_{gt} - \sum_{g=1}^{n_g} y_g * WI_g + f_g * WP_g = 0 \tag{4}$$

where	$y_g * FCI_g + f_g * FCP_g$	is the linearised fuel consumption of gas turbine g as a function of its level of utilitisation
	$y_g * WI_g + f_g * WP_g$	is the linearised mechanical power production of the gas turbine g as a function of the level of utilisation

The values for the linearisation are computed by simulation considering the partial load operation of the gas turbine. For each gas turbine g, the unknowns are f_g, y_g, f_g^{pc} while the other parameters are obtained from the thermo-economic models. The quality of the linearisation will mainly depend on the range in which the part load operation is expected to happen in the optimal situation.

The operating costs OC_{gt} and the investment costs IC_{gt} of the selected gas turbines are computed by :

$$\sum_{g=1}^{n_g} (y_g * OCI_g + f_g * OCP_g) - OC_{gt} = 0 \tag{5}$$

$$\sum_{g=1}^{n_g} y_g * ICI_g - IC_{gt} = 0 \tag{6}$$

where $y_g * OCI_g + f_g * OCP_g$ is the linearised maintenance cost of gas turbine g as a function of its level of utilisation ;

$y_g * ICI_g$ is the investment cost of gas turbine g from the data base catalog;

The fraction of the flue gas of the gas turbine used in the post combustion is limited to the level of utilisation of the gas turbine g.

$$f_g^{pc} \leq f_g \qquad \forall g = 1, n_g \quad (7)$$

The combustion model is made of different equations: (8) includes different terms representing the oxygen balance required by the combustion of the fuels and the oxygen supplied by air and post combustion flue gas.

$$\sum_{g=1}^{n_g} f_g^{pc} * \dot{m}_g * x_g^{O_2} + f_{air} * x_{air}^{O_2} - \sum_{a=1}^{n_a} f_a * \dot{m}_a * x_a^{O_2} - \sum_{c=1}^{n_c} f_c^c * \kappa_c^{O_2} \geq 0 \qquad (8)$$

where $x_g^{O_2}$ is the oxygen content of the flue gas at the outlet of the gas turbine g

$x_{air}^{O_2}$ is the oxygen content of the ambient air

f_{air} is the amount of air used by the combustion in the system

f_c is the flowrate of fuel c, ($f_c \leq f_c^{max}$), its specific cost is C_c

$\dot{m}_c^f$ is the fumes floware resulting from the combustion of fuel c

cp_c^f is the mean specific heat of the fumes resulting from combustion. This cp is considered between $Trad$ and $Tstack$

n_c is the number of fuels that can be used in the system including n_{cgt}

$\kappa_c^{O_2}$ is the oxygen requirement per unit of fuel c. For practical reasons, the oxygen requirement includes the minimum oxygen excess for this fuel

$x_a^{O_2}$ is the oxygen content of the enriched air stream leaving the air separation unit a

$\dot{m}_a$ is the nominal flowrate of enriched air leaving the air separation unit a

f_a is the level of utilisation of air separation unit a, $f_a^{min} * y_a \leq f_a \leq f_a^{max} * y_a$

y_a	is the integer variable representing the use or not (1,0) of the air separation unit a
$f_a^{min(max)}$	is the minimum (maximum) level of utilisation of the air separation unit a
n_a	is the number of air separation units considered in the system

Fuel consumption balance for the fuels that might be used either in gas turbine or in standard combustion.

$$f_c^c + \sum_{g=1}^{n_g} f_c^g - f_c = 0 \quad (9)$$

High temperature balance : radiative exchange model above $Trad$

$$f_c * (LHV_c + (cp_{air} * \frac{\kappa_c^{O_2}}{x_{air}^{O_2}} * (Trad - T_0))) - f_{air} * cp_{air} * (Trad - T_0) - \sum_{a=1}^{n_a} f_a * \dot{m}_a * cp_a * (Trad - TO_a) + Q_{prh} - Q_{rad} = 0 \quad (10)$$

Low temperature balance : convective exchange below $Trad$

$$f_{air} * cp_{air} * (Trad - Tstack) + f_c * (\dot{m}_c^f * cpf_c - cp_{air} * \frac{\kappa_c^{O_2}}{x_{air}^{O_2}}) * (Trad - Tstack) + \sum_{a=1}^{n_a} f_a * \dot{m}_a * cp_a * (Trad - Tstack) - Q_{cnv} = 0 \quad (11)$$

where

Q_{rad}	is the total amount of heat available above $Trad$
Q_{cnv}	is the total amount of heat available from $Trad$ to $Tstack$
LHV_c	is the lower heating value of the fuel c. This value is the value computed by simulation of the combustion using the minimum accepted value of the oxygen content in the fumes
T_0	is the reference temperature used for computing the LHV
T_{air}^{in}	is the inlet temperature of air
Q_{prh}	is the heat load of air preheating, the existence of the air preheating equipment is defined by an integer variable y_{prh} and the following equation :$y_{prh}Q_{prh}^{min} \leq Q_{prh} \leq y_{prh}Q_{prh}^{max}$. The investment cost of the air preheating device is computed by linearising the air preheater cost by $IC_{prh} = ICF_{prh}y_{prh} + ICP_{prh}Q_{prh}$

cp_a is the mean specific heat of the enriched air leaving unit a at a temperature of TO_a.

2.1.2 Air preheating : outlet temperature calculation

In this model, the air preheating temperature is unknown and its optimal value has to be computed. When the heat recovery system is used, the optimal preheating temperature is a non trivial task, since the temperature is used to generate the list of the constraints. This makes the problem non linear and discontinuous (i.e. according to the temperature the stream will appear or not in the heat cascade constraints). Some techniques have been tried to solve this problem as a non linear programming (in our case mixed integer) problem using smooth approximation techniques (e.g. Duran and Grossmann (1986)). Here, we decided to keep the problem linear and continuous by discretizing the temperature range in which the air preheating will take place in n_i intervals of ΔT. The air preheating stream is therefore defined by a list of cold streams from T_i^{air} to $T_{i+1}^{air} = T_i^{air} + \Delta T$ and by adding the following constraints :

$$f_{air} \geq fa_i \qquad \forall i = 1, ..., n_i \tag{12a}$$

$$Q_{prh} = \sum_{i=1}^{n_i} fa_i cp_{air,i}(T_{i+1} - T_i) \tag{12b}$$

with fa_i the flowrate of air preheated from T_i to T_{i+1}.

$cp_{air,i}$ the specific heat capacity of the air flowrate between T_i to T_{i+1}.

In the combustion model, the optimal temperature calculation model is also used to compute the outlet temperature of the air and enriched air preheating, fuel preheating as well as to compute the outlet temperature at the stack. This calculation is made in two steps :

(1) solve the model and compute the optimal flowrates in each interval (fa_i);
(2) compute the resulting temperature To_{n_i} by solving from i =1 to n_i , $To_i = \frac{(fa_{i-1} - fa_i)To_{i-1} + fa_i * T_{i+1}}{fa_{i-1}}$ with $To_0 = Ta_{in}$ the inlet temperature of the stream a.

The precision of the model is related to the size of the discretizing temperature intervals. We have to consider a compromise between the precision required for the equipment sizing and the number of variables. A similar formulation is also used to compute the optimal temperature of the gas turbine flue gas after heat recovery.

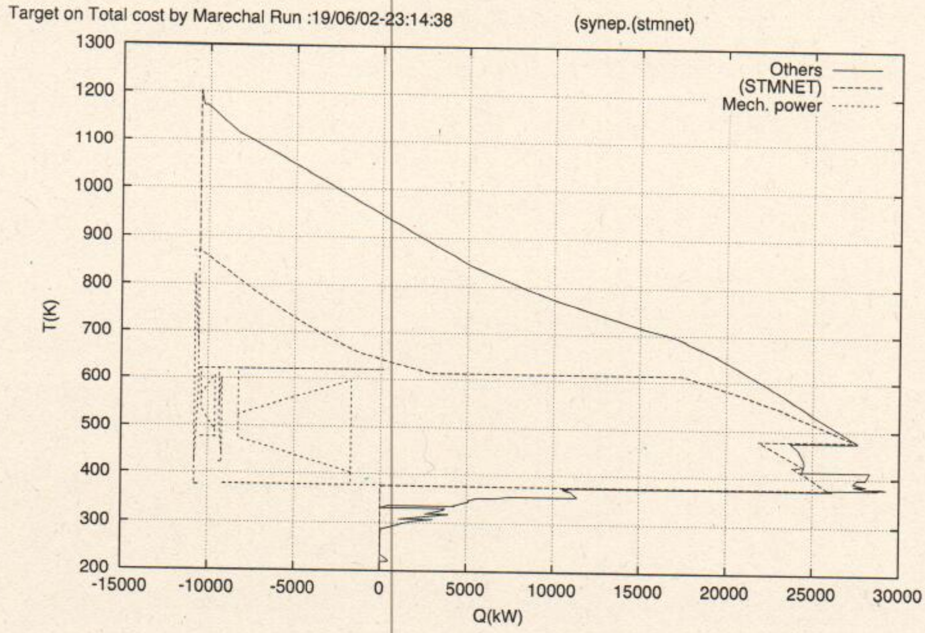

Fig. 4. Integrated composite curves of the steam network of the production site

This systematic choice has been made to keep the robustness advantage of the MILP formulation.

2.2 Application of the model

The set of equations described above is added to the MILP problem formulation used to solve the utility integration targeting problem (Marechal and Kalitventzeff , 1998). Applying this model in the average conditions, we obtained a solution whose integration is represented by the integrated composite curves of figure 4. The interest of the steam network in the system stands in the combined heat and power production but also is the heat transfer from one exothermic process and endothermic ones. The steam network allows also considering the valorisation of the exergetic potential of the total system. In our example, the steam network works with high pressure steam that is produced from the exothermic processes of the chemical industrial site. This is important when considering a gas turbine integration since the gas turbine will not be able to reach a temperature compatible with steam pressure levels shown on figure 4.

3 Multi-period problem

When considering the energy system design and especially when dealing with industrial site process integration, the multi-period approach reveals to be of a great importance because it has to represent the opportunities of integration together with the need of integrating the utility system in an appropriate manner and more specially of considering the combined heat and power production. This problem is even more complex when technologies used in the utility system have to be chosen among a list of fixed size units (e.g. gas turbines or internal combustion engines) and when synergies between technologies (e.g. between a gas turbine, the steam network and the processes) have to be valorized.

The multi-period problem is therefore to select the appropriate technologies, to compute their size and determine the optimal operating strategy that will minimize the total cost of satisfying the yearly requirements of the integrated system. In chapter 2, we did state the state and solve the problem for constant process production specifications. In chapter 3, we will model the global system requirements under varying production scenarios and present our mathematical formulation of the multi-period energy integration targeting problem.

3.1 Multi-period synthesis problem: generic formulation

The use of MI(N)LP problems for solving multi-period process synthesis problems has been reviewed by (Grossmann and Santibanez , 1980) and (Grossmann , 1985). Multi-period optimisation is a well known problem that has been considered mainly in the heat exchanger network design; e.g. (Floudas and Grossmann , 1986), (Floudas and Grossmann , 1987), (Marechal and Kalitventzeff , 1989). The generic problem is formulated as follows :

$$\underset{y_t,x_t,y,s}{Min} \sum_{t=1}^{n_t} t_t * c(x_t, s) + I(y, s) \tag{13}$$

Submitted to :

$$h_t(x_t, s) = 0 \qquad \forall t = 1, ..., n_t \tag{14a}$$
$$g_t(x_t, s) \geq 0 \qquad \forall t = 1, ..., n_t \tag{14b}$$
$$y_t \leq y \qquad \forall t = 1, ..., n_t \tag{14c}$$
$$y_t, y \epsilon \{0, 1\} \qquad \forall t = 1, ..., n_t \tag{14d}$$

where $h_t(x_t, s)$ is the set of modelling constraints during the period t;

$g_t(x_t, s)$	is the set of inequality constraints during the period t;
x_t	is an array representing the operating conditions of the equipments during time period t;
y_t	is an integer variable representing the use or not of an equipment during time period t;
s	is the array of the sizing parameters of the equipment sets, once an equipment is selected (see value of y), it is used throughout all the operating periods;
y	is the array of the integer variables representing the selection of the equipment;
$c(x_t, s)$	is the operating cost during the operating period i;
$I(s, y)$	is the total annualised cost of the equipments of size s;
t_t	is the operation time of period t;

3.2 Identify the multi-period load scenario

In the multi-period synthesis problem formulation, the variables s and y are common to all the periods while the others variables y_t and x_t refer to a given period t. This offers a great flexibility in terms of problem definition and decomposition for the solving procedure. This formulation relies on the decomposition of the overall operating time into a limited number of well chosen operating periods. The most rigorous approach would be to model a complete year of operation day by day or even hour per hour. Unfortunately, this would lead to an unacceptable number of decision variables since the optimal value of each decision (y_t) and the level of operation(x_t) of the selected technologies would have to be computed for each period t. If we assume that no heat storage is considered, the yearly process requirements might be represented by a limited set of requirement levels for each of the processes in the global system. The usual approach (e.g. (Grossmann and Santibanez , 1980)) consists in defining for each of the sub-systems concerned (j), a list of operating period (k, j) identified by a starting ($t_{k,j}^{start}$) and an ending ($t_{k,j}^{end}$) time associated with a level of operation ($L_{k,j}$). Computing over the time horizon (from $t = 0$ to $max(t_{k,j}^{end})$), it is possible to define a finite number of periods p corresponding to a set of $L_{p,j}$ and a given operating time period $t_p = \Delta t_{k,j}^x$.

If this task is rather easy when only one requirement (or process) is considered or when all the variations are simultaneous, the problem becomes much more difficult when different processes are operated independently on the same process site or when the requirements are not simultaneous. Even in this situation, and assuming that each process is represented by a very limited number of operating conditions, the number of periods resulting from the integration of the different processes remains high (figure 2). When no heat storage is envisaged, the number of sets can be reduced because the time sequence is not important anymore meaning for example that nights and days operation can be assembled to form 2 distinct periods with an operating time period corresponding to the sum of the individual periods. If heat storage is considered the method can not be used because is this case, the level of the heat storage will vary with time and the sequence of operations will have to be maintained. If more than one process is considered the simultaneity of the operations has to be considered and summation is not necessarily possible due to the different nature of the process requirements.

To tackle the problem, an optimisation problem (15) has been set up. It consists in defining the optimal value of n_p specified production sets of n_j sub-system levels $L_{j,p}$ that will represent the levels of operation of sub-system j in the set p. We should note that in this approach the variable $L_{j,p}$ may also be used to represent the variation of a price condition (e.g. electricity). When different operating modes exist for one process (e.g. production /cleaning) two different sub-systems will be considered. The problem formulation is the following :

$$min_{L_{j,p}} \sum_{t=1}^{n_t} \left\{ \min_{p=1,\dots,n_p} \sum_{j=1}^{n_j} \left(\frac{L_{j,p} - q_{j,t}}{\omega_j} \right)^2 \right\} \tag{15}$$

where $q_{j,t}$ is the production level of sub-system j during the time period t;

ω_j is a weight factor that allows comparing the production levels of sub-system j with the other sub-systems;

$L_{j,p}$ is the production level considered for sub-system j in the set p;

n_t is the number of time periods in process measurements;

n_p is the number of specified production sets;

n_j is the number of independent sub-systems considered.

Literally this mathematical formulation tries to find the values of n_p sets of n_j sub-system levels that minimize the error between the estimated requirement $L_{j,p}$ and the observed one $q_{j,t}$ over the observed period. The operating time t_p corresponding to the set p is obtain by summing up the t_t times the $L_{j,p}$ are selected. This optimisation problem is a least square non linear unconstrained, min-min problem that is by definition multi-modal and discontinuous optimisation problem, discontinuous because of the min-min problem and multi-modal because the sets p can be permuted without affecting the solution . The resolution of the problem is therefore not so easy. A genetic algorithm (Leyland , 2002) has been used to solve this problem and gave satisfactory results, that are shown on figure ?? where dotted lines represent the load scenario model with $n_p = 10$ sets of simultaneous levels. Replacing the n_t t_t periods by the n_p t_p periods, the dimension of the problem 13 becomes smaller.

The variations of the process production levels has been identified solving the min-min optimisation problem. The results of the integration period by period are given on table 3 where "Li" are the 10 period levels obtained, "MER hot" is the heat to be supplied to the system, "MER cold" is the heat to be removed by the cooling water system and "MER frg" refers to the heat to be removed by a refrigeration system.

Table 3
Minimum energy requirements and levels of operations in the different periods

	MER hot (kW)	MER cold (kW)	MER frg (kW)	time h/year
L1	22581.	0.	155.	432
L2	0.	18119.7	1027.8	48
L3	19814.	987.	347.	192
L4	10146.	1411.	380.	264
L5	27771.	0.	0.	720
L6	13311.	4897.	751.	144
L7	0.	10526.	677.	240
L8	12252.	173.	311.	1224
L9	7061.7	831.	310.	2904
L10	8539.	577.	278.	2592
Average	10270.	385.6	261	8760.

Considering the multi-period strategy, we observe that the process requirements vary with time from a supply of 27771 kW to a production of 18120 kW in exothermic conditions. This is due to the relative level of usage of exothermic and endothermic processes.

3.3 Mathematical formulation of the multi-period utility system targeting problem

In this paper, we describe the adaptation of the utility system synthesis to multiperiod problems where we consider simultaneously utility system, heat recovery system and combined heat and power production. The model for representing one period of operation (Li) is given above in chapter 2, below we generalize the formulation representing the level of utilisation of each utility system technology by the generic integer variables y_w representing the existence of the technology w and f_w the level of utilisation. The multi-period system creates variables y_w^p and f_w^p for each operating period p. The objective function is the total cost including the operating costs and the annualised investment cost both expressed in Monetary Units (MU) per year. The annualising factor is computed from the annualising rate and the life time of the investment. In case of load variations, we have to determine in each time period the extend of use of the technology (partial load operation) to satisfy the requirements of the whole industrial site. In the equation system (16), we represent the Effect Modelling and Optimisation (EMO) models by an additional set a constraints that are written in a generic form.

$$\min_{R_r^p, y_w^p, f_w^p y_w^{max}, f_w^{max}} \sum_{p=1}^{n_p} \sum_{w=1}^{n_w} (C2_w^p f_w^p) + Cel^p Wel^p - Cel_v^p Wel_s^p * t_p$$
$$+ \sum_{w=1}^{n_w} (C1_w y_w^{max}) + \frac{1}{\tau} \sum_{w=1}^{n_w} (ICF_w y_w^{max} + ICP_w f_w^{max}) \quad (16)$$

subject to

Heat balance of the temperature intervals

$$\sum_{w=1}^{n_w} f_w^p q_{w,r} + \sum_{i=1}^{n} Q_{i,r} * L_{i,p} + R_{r+1}^p - R_r^p = 0 \qquad {}_{\forall r=1,\dots,n_r}^{\forall p=1,\dots,n_p} \quad (17)$$

Electricity consumption:

$$\sum_{w=1}^{n_w} f_w^p w_w + Wel^p - L_{c,p} * Wc \geq 0 \qquad \forall p = 1, ..., n_p \quad (18)$$

Electricity exportation

$$\sum_{w=1}^{n_w} f_w^p w_w + Wel^p - Wel_s^p - L_{c,p} * Wc = 0 \qquad \forall p = 1, ..., n_p \quad (19)$$

Other additional constraints

$$\sum_{w=1}^{n_w} a_x^{i,p} f_w^p + c_w^{i,p} y_w^p + \sum_{k=1}^{n_x} d_k^{i,p} x_{k\geq}^{t=} = b_i^p \qquad {\scriptstyle \forall i=1,\ldots,n_e \atop \forall p=1,\ldots,n_p} \quad (20)$$

$$xmin_k \leq x_k^p \leq xmax_k \qquad {\scriptstyle \forall k=1,\ldots,n_x \atop \forall p=1,\ldots,n_p} \quad (21)$$

Existence of operation w during the time period p:

$$fmin_w y_w^p \leq f_w^p \leq fmax_w y_w^p \qquad {\scriptstyle \forall w=1,\ldots,n_w \atop \forall p=1,\ldots,n_p} \quad (22)$$

$$y_w^p \in 0, 1 \qquad (23)$$

Thermodynamic feasibility of the heat recovery and utility systems

$$Wel^p \geq 0, Wel_s^p \geq 0 \qquad (24)$$

$$R_1^p = 0, R_{n_{r+1}}^p = 0, R_r^p \geq 0 \qquad {\scriptstyle \forall r=1,\ldots,n_{r+1} \atop \forall p=1,\ldots,n_p} \quad (25)$$

Maximum size of operation w

$$f_w^{max} - f_w^p \geq 0_{\forall p=1,\ldots,n_p}^{\forall w=1,\ldots,n_w} \qquad (26)$$

$$x_k^{max} - x_k^p \geq 0_{\forall p=1,\ldots,n_p}^{\forall k=1,\ldots,n_x} \qquad (27)$$

Use or not of operation w

$$y_w^{max} - y_w^p \geq 0 \qquad {\scriptstyle \forall w=1,\ldots,n_w \atop \forall p=1,\ldots,n_p} \quad (28)$$

with n the number of specified process streams;

n_r the number of temperature intervals;

R_r^p the energy cascaded from the temperature interval r to the lower temperature intervals in the time period p;

Q_{ir} the heat load of the reference level of process stream i in the temperature interval r; $Q_{ir} > 0$ for hot streams and ≤ 0 for cold streams;

$L_{i,p}$ the level factor of use of stream i during the time period p;

n_w the number of technologies proposed in the super configuration of the utility system;

n_p the number of time period in the problem;

q_{wr} the heat load of the technology w in the temperature interval r for a given reference flowrate, $q_w r > 0$ for a hot stream;

f_w^p the multiplication factor of the reference flowrate of the technology w in the optimal situation during the time period p;

w_w the mechanical power produced by the reference flowrate of technology w; $w_{w,t} < 0$ for a mechanical power consumer and > 0 for a producer;

Cel_s^p the selling price of electricity during the time period p;

Wel_s^p the net production of electricity during the time period p;

Cel^p the electricity cost during the time period p;

Wel^t the net import of electricity during the time period p;

Wc the overall mechanical power needs of the process; $Wc < 0$ if the overall balance corresponds to a mechanical power production

x_k^p the (n_x) additional variables used in the additional equations of the technology models for time period p.

$\substack{a_w^{i,p} \\ c_w^{i,p}}$ respectively $\substack{\text{the coefficients of the multiplication factor} \\ \text{the integer variables}}$ of technology w in the constraint i in the effect models during the time period p.

$\substack{d_k^{i,p} \\ b_i^p}$ respectively the $\substack{\text{coefficients of the additional variables} \\ \text{the independent term}}$ in the constraint i in the effect models during time period p;

$\substack{xmin_r \\ xmax_r}$ respectively the $\substack{minimum \\ maximum}$ bounds of x_r.

$\substack{fmin_w \\ fmax_w}$ the $\substack{minimum \\ maximum}$ values accepted for f_w^p

y_w^p the integer variable associated with the use of the technology w during the time period p;

$C1_w$ the fixed cost of using the technology w, this value is expressed in monetary units (MU) per year;

$C2_w^p$ the proportional cost of using the technology w during the time period p. This value is defined in MU/unit of time period;

ICF_w the fixed cost related to the investment of using operation w; ICF_w is expressed in Monetary Units (MU) and refers to the investment cost of the combustion and cogeneration equipments as defined above as well as to the other equipments considered in the utility system (turbines, heat pumps, refrigeration systems,...).

ICP_w the proportional cost related to the investment of using the operation w, ICP_w is expressed in MU/(unit of w).

τ is the annualising factor of the investment. This value is used to express the investment of the IEST's in MU/year. $\tau = \frac{(1+i)^{n_{years}-1}}{i(1+i)^{n_{years}}}$ is the annualisation factor of the investment ($years^{-1}$) for a annualisation interest i and an expected equipment life n_{years}.

y_w^{max} the maximum value of the integer variable associated with the use of the operation w over the overall the time period. If the operation w is used at least once during the overall time period the value of y_w^{max} is equal to 1 and the related investment will be considered as well as the related fixed operating cost.

f_w^{max} the maximum value of the multiplication factor of operation w over the overall the time period. This value represents the (maximum) size of the technology to be installed and is therefore related to the investment for the corresponding IEST.

t_p the total operating time of period p.

The developments have been made in such a way that for each time period the same MILP problem is generated. The equations for computing the maximum sizes and the objective function are added after a loop for the n_p time periods. For generating multiple solutions, the integer cut constraints (i.e.(Duran and Grossmann , 1986)) will act on the y_w^{max} variables. The equation will be in the following form :

$$ProblemMILP_k \tag{29}$$

$$\sum_{j=1}^{n_y}((2(y_j^{max})^k - 1)y_j^{max}) \leq \sum_{j=1}^{n_y}((y_j^{max})^k - 1) \tag{30}$$

with $(y_j^{max})^k$ the value of the integer variable y_j^{max} in the solution of problem k;

n_y the number of alternatives to be studied.

3.4 The limitations of the approach

The proposed approach does not allow to compute heat storage between two time periods. This would require additional equations to compute the overall amount of heat to be stored. In this case the method for identifying the time periods can not be applied since the sequence of the operations has to be considered. In this case, the size of the MILP problem will increase consequently.

The approach proposed uses a linearized partial load efficiency computed by simulation, iterative sequence of calculations might be used to verify the optimality of the solutions proposed.

The size of the problem increases when the number of periods increases since it consists in n_p MILP problems concatenated and requires efficient large scale MILP algorithms. Let us remark that there are only little relations between the different sub-sets of the problem, the link between the different time periods being obtained by the definition of y_w^{max} and f_w^{max}. This means that when the objective function is the operating cost and that no fixed cost is considered or when the objective function is the minimum exergy losses, the results will be obtained by solving the problem successively for the different time periods and by summing up the different objective functions obtained. If the total cost is used as an objective function or if fixed cost are used to define the operating cost, the method presented here above can be safely used.

4 Application

The size of the problem stated in the introduction with 10 time periods sets is of 1900 constraints and 1600 variables including 40 integer variables. Table 4 gives the electricity production, the fuel consumption and the total cost of the different solutions found. The column " CHP eff " represents the marginal efficiency of the electricity power production. It is computed by the ratio between the electricity production and the extra fuel consumed for this production, i.e. $\frac{El(MWh_e)}{Fuel(MWh)-\frac{Mer(MWh)}{\eta_{th}}}$ with $\eta_{th} = 95\%$ the efficiency of a conventional boiler. We should note here that choosing an efficiency of 90 % rather then 95% would lead to efficiencies higher than unity for some of the solutions. These high values of marginal efficiencies are explained by the steam network production that valorises the exergy potential of the exothermic processes. The heat from the processes is used to produce high pressure steam that is expanded and then used in other processes above the pinch. According to the optimal CHP placement rule (Townsend D.W., Linnhoff B. , 1983), above the pinch, one fuel heat unit per unit mechanical power produced. When the utility system is considered, the additional unit of fuel heat is the heat supplied by the combustion of one unit of fuel, therefore the efficiency is lower than one in terms of lower heating value. In case of the gas turbine, the fuel heat of the gas turbine is the heat available in the fumes cooled down from Q_g^{gt} (1), that is itself related to a supplement of mechanical power produced W_{gt} (4). In the results presented in table 4, more than one solution is presented for the same gas turbine.

These cases have been computed by varying the price of the electricity. In table

4, the results are presented for the same price of Electricity for comparison purposes. For low prices of electricity, the gas turbine is not used in all the periods : it is shut down during periods where the process is not requiring heat (solution GTx_{low}). When the electricity price is higher (solution GTx_{int}), the gas turbine is always used and the post combustion fuel is adapted to satisfy the heat requirements of the whole plant. The gas turbine is used even during periods where there is no heat to supply to the process. In this case, the extra amount of steam produced by the gas turbine is expanded in a condensing steam turbine. For higher prices of electricity (GTx_{high}), the gas turbine is always used at its maximum as well as the post combustion such that the maximum production of electricity is reached by expanding high pressure steam in the condensing turbine.

Table 4
Results with different gas turbines, Natural gas price : 0,135 ϵ/kg, Electricity : $35\epsilon/MWh$(high)

	Electricity (MWh)	Fuel (MWh)	Total cost $\epsilon/year$	CHP Eff (%)	Comments
$GT3_{low}$	116494	248996	263893	78.6	GT shut down
$\mathbf{GT1_{int}}$	**90303**	**210622**	**-226811**	**82.2**	**Min post combustion**
$GT3_{int}$	143949	304960	-78213	70.5	Min post combustion
$GT4_{int}$	113220	243344	-220005	79.4	Min post combustion
$GT1_{high}$	139690	356721	-377481	54.7	Max post combustion
$GT2_{high}$	137665	354075	-209181	54.4	Max post combustion
$GT3_{high}$	192503	451327	-196827	54.9	Max post combustion
$GT4_{high}$	166219	400155	-381427	55.5	Max post combustion

The detailed results of the system integration for the case $GT1_{int}$ are summarised in table 5 where we present the yearly electricity production of the gas turbine, the power of the CHP production, the total combined heat and power yearly production, as well as the fuel consumption and the CHP efficiency. To illustrate the combined production of electricity by the condensing turbine, we give also the computed flowrate in the condensing stage of the steam turbine. The use of the condensing turbine in period L2 explains by the fact that the process is a threshold problem with an excess of heat to be evacuated from the process (see table ??). This excess of energy is therefore used to produce mechanical power in the condensing turbine.

The solution presented here allows to illustrate the interest of the approach, we identify that the gas turbine is profitable especially by the use of the combined heat and power production from the steam network. It should be observed that for period where the processes are exothermic, the gas turbine is used and a condensing level is considered for the steam turbine in order to maximise the electricity production. The comparison between $GT4$ et $GT1$ solutions is interesting : for medium prices of electricity, the best solution is $GT1_{int}$ that is smaller while if the electricity price is increased, the best solution is $GT4_{high}$. This illustrates the interest of generating multiple solutions rather than searching just for a unique solution. Sensitivity analysis will therefore be required to identify the best solution.

5 Discussion

Some difficulties have been observed when using this approach. In order to make it work properly, one has to use a coherent data set for computing the objective function. We stress here on the importance of the relative value of electricity and fuel prices with respect to the investment cost. We observed situations where the marginal cost of producing electricity by the gas turbine becomes smaller than zero. In this case, as we are working with a linear programming system, the solution is the use of **all** the gas turbines at the maximum for the whole year. This solution just says that the marginal efficiency of the gas turbine combined with the steam turbine without considering the cogeneration becomes profitable to produce electricity at the selected price.

Table 5
Details of the solution computed with $GT1_{int}$

	GT (MWh)	CHP power kW	CHP total (MWh)	Fuel (MWh)	CHP Efficiency (%)	Condensing kmol/s
L1	2382	11493	4965	15867	88.7	0.013
L2	265	13660	656	808	81.1	0.34
L3	1059	10879	2089	6457	85.2	0.0
L4	1456	8407	2219	5618	79.3	0.0
L5	3970	12404	8931	30971	90.0	0.02
L6	794	10775	1552	3900	82.4	0.0
L7	1323	11178	2683	4043	66.3	0.27
L8	6750	10379	12704	30735	85.0	0.0
L9	16015	10158	29499	57981	81.1	0.0
L10	14295	9647,6	25006	54240	80.8	0.0
Total	**48311**		**90303**	**210622**	**82.2**	

On figure 5, we show the total cost of three situations resulting from the use of the same gas turbine ($GT3$). This shows that according to the price of electricity different solutions are optimal. This renders the use of strict optimisation procedure very difficult : sensitivity analysis combined with the multiple solutions generation should therefore be used. A more pragmatic approach being to solve for a given set of selected technologies a sequence of minimum operating cost problems for different values of the electricity prices, each problem being solved independently for each of the considered periods.

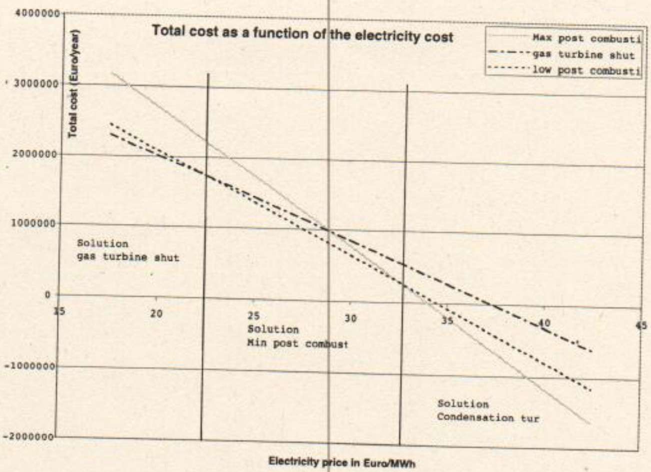

Fig. 5. Cost of the different solutions as a function of the electricity selling price, Natural gas price : 0,135 ϵ/kg

6 Conclusion

A mixed integer linear programming formulation has been presented and applied to solve the optimal integration of the utility system of an industrial production site. The method developed addresses the problem of solving a multi-period optimisation problem that incorporates models for selecting and targeting the optimal operation strategy of the utility system including gas turbines, steam network and cooling system together with the calculation of the optimal heat recovery system. The identification of the operating periods has been made by using a genetic algorithm method that computes a set of simultaneous levels of utilisation for each of the processes under study. The gas turbine and combustion model has been developed to handle existing gas turbines available on the market. The model uses data from technology data bases, simulation to represent the partial load performances in each of the operating periods. The MILP model proposed allows to compute the optimal flows to be considered in the integrated system and especially computing the optimal flows to be considered in the steam network and in the post combustion system.

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